PB90-186123

Evaluation Paradigm for Cumulative Impact Analysis

(U.S.) Army Engineer Inst. for Water Resources, Fort Belvoir, VA

Prepared for:
Corvallis Environmental Research Lab., OR

1988

U.S. Department of Commerce
National Technical Information Service
NTIS

ERL-COR-874J

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/600/J-88/505	2.
3. RECI PB90-186123	
4. TITLE AND SUBTITLE An evaluation paradigm for cumulative impact analysis	5. REPORT DATE 1988
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Eugene Z. Stakhiv	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Corps of Engineers, Fort Belvoir, VA	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS US Environmental Protection Agency Environmental Research Laboratory 200 SW 35th Street Corvallis, OR 97333	13. TYPE OF REPORT AND PERIOD COVERED Journal Article
	14. SPONSORING AGENCY CODE EPA/600/2

15. SUPPLEMENTARY NOTES

In Special Issue -Environmental Management 12(5):725-748. 1988 Sept.

16. ABSTRACT

Cumulative impact analysis is examined from a conceptual decisionmaking perspective, focusing on its implicit and explicit purposes as suggested within the policy and procedures for environmental impact analysis of the National Environmental Policy Act of 1969 (NEPA) and its implementing regulations. In this paper it is also linked to different evaluation and decisionmaking conventions, contrasting a regulatory context with a comprehensive planning framework. Finally, the specific problems that make the application of cumulative impact analysis a virtually intractable evaluation requirement are discussed in connection with the regulation of wetlands uses through the Corps of Engineers' permit program, in conjunction with the Environmental Protection Agency's responsibilities in managing its share of the "Section 404" regulatory program requirements.

To understand the purposes of cumulative impact analysis (CIA), a key distinction must be made between the implied comprehensive and multiobjective evaluation purposes of CIA, promoted through the principles and policies contained in NEPA, and the more commonly conducted and limited assessment of cumulative ecological effects (ACE), which focuses almost entirely on the ecological effects of human actions. Based on current evaluation practices within the Corps' and EPA's permit programs, it is shown that the commonly used screening approach to regulating wetlands uses is not compatible with the purposes of CIA, nor is the environmental impact statement (EIS) an appropriate vehicle for evaluating the variety of objectives and trade-offs needed as part of CIA. A heuristic model that incorporates the basic elements of CIA is developed, including the idea of trade-offs among social, economic, and environmental protection goals carried out within the context of environmental carry capacity.

→ PG 425

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 25
	20. SECURITY CLASS (This page) Unclassified	22. PRICE A03

EPA Form 2220-1 (9-73)

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL INFORMATION SERVICE
SPRINGFIELD, VA. 22161

EPA/600/J-88/505

An Evaluation Paradigm for Cumulative Impact Analysis

EUGENE Z. STAKHIV
US Army Corps of Engineers
Institute for Water Resources
Fort Belvoir, Virginia 22060, USA

ABSTRACT / Cumulative impact analysis is examined from a conceptual decision-making perspective, focusing on its implicit and explicit purposes as suggested within the policy and procedures for environmental impact analysis of the National Environmental Policy Act of 1969 (NEPA) and its implementing regulations. In this article it is also linked to different evaluation and decision-making conventions, contrasting a regulatory context with a comprehensive planning framework. The specific problems that make the application of cumulative impact analysis a virtually intractable evaluation requirement are discussed in connection with the federal regulation of wetlands uses. The relatively familiar US Army Corps of Engineers' (the Corps) permit program, in conjunction with the Environmental Protection Agency's (EPA) responsibilities in managing its share of the Section 404 regulatory program requirements, is used throughout as the realistic context for highlighting certain pragmatic evaluation aspects of cumulative impact assessment.

To understand the purposes of cumulative impact analysis (CIA), a key distinction must be made between the implied comprehensive and multiobjective evaluation purposes of CIA, promoted through the principles and policies contained in NEPA, and the more commonly conducted and limited assessment of cumulative effects (ACE), which focuses largely on the ecological effects of human actions. Based on current evaluation practices within the Corps' and EPA's permit programs, it is shown that the commonly used screening approach to regulating wetlands uses is not compatible with the purposes of CIA, nor is the environmental impact statement (EIS) an appropriate vehicle for evaluating the variety of objectives and trade-offs needed as part of CIA. A heuristic model that incorporates the basic elements of CIA is developed, including the idea of trade-offs among social, economic, and environmental protection goals carried out within the context of environmental carrying capacity.

The dominant evaluation and decision-making perspectives driving current interpretations and approaches to cumulative impact analysis are related to a conventional and limited reading of the National Environmental Policy Act (NEPA 1969), i.e., emphasis on environmental impact analysis as the process for highlighting the ecological aspects of the human environment. The analytical or measurement criteria that normally complement this orientation stress a "scientific" (i.e., objective, deterministic) approach to problem solving. Thus, in the search for a cumulative impact analysis (CIA) evaluation paradigm for valued enviromental resources such as wetlands, the emphasis has been on tracing the accumulated effects of numerous and diverse perturbations throughout an ecosystem. For example, the National Research Council's study (NRC 1986), "Ecological Knowledge and Environmental Problem-Solving," focused solely on ecological systems, without concern for social and economic aspirations. The NRC study listed the elements of an assessment of cumulative environmental effects as time-crowded perturbations, space-crowded perturbations, synergism, indirect effects, "nibbling" or incremental degradation of the environment, and delayed effects on the natural environment.

Preston and Bedford (1988) have followed the prescriptions of the NRC, focusing on the technical or scientific part of cumulative impact analysis as it relates to wetlands. These authors wish to understand how wetland ecosystems respond to multiple disturbances. They recognize that there are major evaluation and analytical components to cumulative impact analysis, reflected in the NEPA definition, other than a narrow orientation towards natural systems. These include the procedural–legal requirements as well as the multiple objectives and trade-offs between socioeconomic well-being and environmental quality.

However, the more limited assessment of cumulative disturbance effects on a single resource or ecosystem should not be confused with the broader purposes and evaluation implications of CIA as envisioned by the creators of NEPA (1969) and the subsequent NEPA procedural guidelines of the Council on Environmental Quality (CEQ 1978). The purpose of this discussion is to differentiate between two concepts that

KEY WORDS: Cumulative impact analysis; Regulatory evaluation; Planning decision making; Assessment of ecological effects; Wetlands values; Public interest review; Optimization

Environmental Management Vol. 12, No. 5, pp. 725–748

© 1988 Springer-Verlag New York Inc.

complement each other: assessing the effects of disturbances on natural systems and appraising the impacts in the context of societal objectives. A better understanding is needed of the role of wetlands in ecosystems and biomes and of how disturbances and perturbations caused by population growth and economic development affect the quality and vitality of the natural environment. Ultimately, this knowledge can be translated into an environmental awareness or value set that will drive public decision making.

The distinction between "facts" and "values," between "effects" and "impacts," between "assessment" and "evaluation," indicates the difference between assessment of cumulative effects (ACE), as a scientific, determinate activity that meets the narrowly defined prescriptions of an environmental impact statement, and cumulative impact analysis (CIA), which fulfills the multiobjective, comprehensive planning view of NEPA. Even if scientists were able to provide perfectly accurate information about the ecological consequences of human actions, exclusionary choices would still have to be made among competing social, economic, and environmental objectives. Definitive knowledge about adverse environmental impacts does not mean that human activities will cease. Facts and subjective values both serve as the basis for trade-offs among competing resource uses and environmental management goals. A large number of environmental protection objectives have enjoyed such widespread public support that they have become codified as, for example, laws protecting endangered species and wild and scenic rivers. Public sentiment about environmental resources, however, is more often couched in terms of protecting or conserving these resources to the maximum extent practicable. Most wetlands fall into this large category of resources that merit special attention and should be conserved, rather than protected absolutely.

Under this situation, wetlands conservation (protection, management) should be thought of as a goal to be achieved in conjunction with other valid socioeconomic needs rather than as an inviolable preservation constraint (Walker 1973, 1974). The knowledge gained from the research proposed in this volume may well result in the development of a set of proposed wetlands resource use constraints. But even enacting resource use constraints as policy or law requires some semiquantitative accounting of social benefits and costs and at least a few political trade-offs. These constraint-setting trade-offs are usually achieved at the programmatic level through the political process, or at the local bureaucratic level on a project or action-specific basis. In the absence of specific wetlands preservation criteria, the concepts and perspectives related to cumulative impact analysis fall into this latter category.

The basic purposes of CIA are much more compatible with anticipatory comprehensive planning than with regulatory decision making, which is characterized by incremental, site-specific, and immediate decision making. Given the accepted NEPA definitions of CIA, decisions related to cumulative impacts can be made only on the basis of forecasts about future activities and their relationship to social, economic, and environmental goals. An impact should be judged only in relation to current and future social needs, acting within a set of physical and environmental constraints. This evaluation perspective comprises the fundamental component of a planning approach. The NEPA implementing guidelines confirm this anticipatory planning view by stating that:

> "Cumulative impact" is the impact on the environment which results from the incremental impact of the action when added to other *past, present, and reasonably foreseeable future actions* regardless of what agency (Federal or non-Federal) or person undertakes such other actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time [40 CFR 1508.7, CEQ 1978] [emphasis added].

The US Army Corps of Engineers' permit program includes the regulation of dredge and fill activities in the nation's waterways, shore zone, and wetlands and provides a realistic and exceedingly complex context for the examination of cumulative impact analysis requirements. It reflects a common regulatory evaluation–decision model, however, where the many decision rules and screening criteria are predetermined. Conceptually, the differences in philosophy between an objectives-oriented planning and a constraint-oriented regulatory evaluation framework are subtle. Ideally, if all the information could be specified correctly, the outcomes should be identical. Realistically, however, decisions may differ substantially, underlining the need to consider a more eclectic, robust multiobjective planning and evaluation approach.

Cumulative impact analysis attempts to overcome the limitations inherent in the "tyranny of small decisions" (Kahn 1966) as well as the "tragedy of the commons" (Hardin 1968). It reflects an assessment and evaluation philosophy that transcends the procedural nature of conventional impact analysis. CIA must encompass not only the consequences of actions, but also the causes, as well as possible management policies. CIA thus must contend with the difficulty of balancing social needs and environmental constraints with an incomplete knowledge base.

From this brief overview, we can see the complexity

of making a cumulative impact analysis of wetlands losses using an existing federal regulatory program. While other articles in this volume focus on the scientific basis for assessment, this article will deal with current impediments to pragmatic evaluation and decision making in this area. They include: (1) nomenclature; (2) purposes of cumulative impact analysis; (3) elements of cumulative impact analysis; (4) regulatory constraints on CIA; (5) wetlands functions, attributes, and values; (6) components of an evaluation paradigm; and (7) evaluation methods for CIA. A number of different issues will be discussed in relation to each topic in an attempt to link CIA with existing procedures and possible new approaches. A heuristic model is also presented that shows how CIA may be structured for an idealized regulatory strategy for wetlands based on the specification of socioeconomic objectives and physical constraints.

Nomenclature

As is often the case with new and increasingly complex problems, lack of precision in the development and use of terminology is common. Preston and Bedford (1988), for example, recognize that a distinction should be drawn between "effects" and "impacts." This distinction reflects an intentional separation between scientific assessment of facts (effects), and the evaluation of the relative importance of these effects by the analysts and the public (impacts).

The evolution of the environmental impact statement as a decision-aiding document has made impact assessment and evaluation increasingly complex, leading to a refinement of evaluation concepts and their associated terminology. The regulations for implementing NEPA (CEQ 1978), for example, expressly state that "effects and impacts as used in these regulations are synonymous" [Section 1508.8(b)]. However, although the terminological distinctions raised here (and elsewhere in this volume) may not be officially accepted, they are used commonly throughout the literature and are useful in the context of this exposition.

Clark and Terrell (1978) conducted a comprehensive environmental study of offshore oil and gas exploration and drilling activities; in current NEPA terminology their study would be considered a programmatic environmental impact statement (EIS). Their nomenclature is largely based on the distinction between the two key components of enviromental analysis: assessment of causes and effects (measuring the magnitude and incidence of perturbations) and evaluation (determining the relative importance of an effect in terms of its fulfillment of human needs).

Table 1. Definition of cause and effect elements of environmental impact cycle.[a]

Element	Definition
Program	A broad initiative taken to fulfill some human need or needs such as offshore oil recovery, middle-income housing, or outdoor recreation.
Project	A specific physical element of a program such as a refinery, crew base, housing subdivision, or marina.
Subproject	A discrete physical component of a project such as site preparation, a bulkhead, or pier.
Construction activity	An individual work process involved in the construction of a project facility such as land clearing or dredging.
Operations activity	An individual work process in the continuing operation of a project such as pumping oil or discharging wastes.
Environmental disturbances	An ecosystem perturbation caused by a disturbance activity such as toxic discharge or elimination of wetlands.
Ecological effect	A reaction of an ecosystem to a disturbance such as oxygen depletion, turbidity, or siltation.
Environmental impact	An environmental alteration that affects the fulfillment of human needs.

[a]From Clark and Terrell, 1978.

Table 1 outlines the *impact cycle* as defined by Clark and Terrell. The impact cycle reflects a common project-analysis approached used by federal agencies. The analytical component of the impact cycle, or scientific part of the analysis, is termed *assessment*. This is true in much of the water-resources planning literature as well as the literature dealing with decision or choice theory. *Evaluation*, on the other hand, applies to the significance or importance of an impact, defined by Clark and Terrell as "an environmental alteration that affects the fulfillment of human needs." The significance of an effect can be judged in relation to two common benchmarks: the constraint, or lowest acceptable level, and the objective, the most desirable level. A major component of human needs includes the preservation and conservation of the environment. These needs are tangibly expressed as goals, objectives, and standards in legislation, executive orders, regulations, and community development plans and zoning ordi-

nances, as well as in the form of subjective community values and preferences. Theoretically rigorous analytical methods are available to assist the more subjective and preference-oriented component of evaluation (e.g., Cohon 1978, Keeney and Raiffa 1976).

Another useful distinction could be made to incorporate the idea of cumulative consequences rather than impacts. Webster's dictionary (College Edition, 1966) differentiates between effect and consequence stating that "effect is applied to that which is directly produced by an action, process, or agent and is the exact correlative of cause; consequence suggests that which follows something else on which it is dependent in some way, but does not connote as direct a connection with cause." This subtle distinction is appropriate for the typical undefinable synergistic and indirect effects that dominate the analysis of cumulative consequences. For the time being, however, it is appropriate to retain the conventional useage of the term cumulative impact analysis, even though the applications, as evidenced in the literature, most frequently deal with the scientific assessment of cumulative consequences on a particular resource.

A larger lexicon of terms is used to characterize the vast diversity of cumulative effects themselves. Such terms as synergistic, interactive, crescive, time-crowded, etc., need better definition, but in the meantime we must contend with terminological imprecision. In contrast to much of the literature on cumulative impact analysis, Vlachos and Hendricks (1976) include both cumulative ecological consequences and the social and economic causes and consequences of environmental degradation. An attempt is made in Figure 1 to summarize many of the ideas and terms related to the assessment of cumulative effects (ACE) or impacts as reflected in the current literature, outlining the philosophical differences between impacts and consequences. Vlachos and Hendricks also focused on the causative agents of cumulative impacts as part of a feedback loop. The difficulty, of course, is in explicating the multidimensional nature of cumulative impacts and measuring the magnitude, timing, and intensity of perturbations through the ecosystem as these effects are caused by, and ultimately affect, the human environment. CIA must take into account the totality of actions and consequences for both social and natural systems as they interact with each other.

Purposes of Cumulative Impact Analysis

NEPA implementing regulations state that "the 'Human Environment' shall be interpreted comprehensively to include the natural and physical environment and the relationships of people with that environment" (40 CFR 1508.14, CEQ 1978). Adverse cumulative impacts, then can be viewed as those environmental consequences judged to be harmful to the ". . . conditions under which man and nature can exist in productive harmony, and fulfill the social, economic, and other requirements of present and future generations . . ." [Section 101(a), NEPA 1969]. The framework of cumulative impact analysis should enable assessment of the impact sequence of causes, perturbations, and effects and evaluation of their environmental as well as social and economic significance. As part of CIA, we should be able to use social-environmental feedback effects as a measure of the effectiveness of alternative management practices.

However, cumulative impacts have been presented in abstract terms (synergistic, indirect, interactive), in terms of measurement (time-crowded, space-crowded), or as examples of systemic changes (acid rain, "greenhouse" warming, wetlands loss). With the exception of Vlachos and Hendricks' (1976) work, the emphasis has been on environmental perturbations rather than on human consequences. Most of what has been written about cumulative human actions, e.g., "nibbling" effects, has focused on water-quality changes.

An instructive assessment of all federal programmatic level activities, policies, and financial and economic incentives that affect wetlands uses was conducted by the US Congress' Office of Technology Assessment (OTA) (US Congress 1984). This comprehensive study dispelled several myths about the contribution of the Corps' regulatory program to "nibbling" and its relation to the substantive causes of wetlands destruction. The study further concluded that the Corps' regulatory program worked rather well given all the legislatively mandated evaluation and decision constraints.

The Corps can be used as an example of a typical regulatory agency responsible for a narrowly limited environmental protection program. The Corps controls only a small fraction of total wetlands acreage and is not responsible for the large annual losses of wetlands caused by agricultural conversion. It must contend with, but cannot counteract, built-in tax incentives and subsidies that encourage wetlands conversion. Farmers, for example, benefit from a range of indirect federal tax incentives and subsidies and direct agricultural supports that encourage the conversion of wetlands to agricultural us (US Congress 1984, Barnard and others 1985). A number of agricultural economists (Shulstad and May 1979, Shabman 1980, Barrows and others 1982, Stavins 1987) have shown

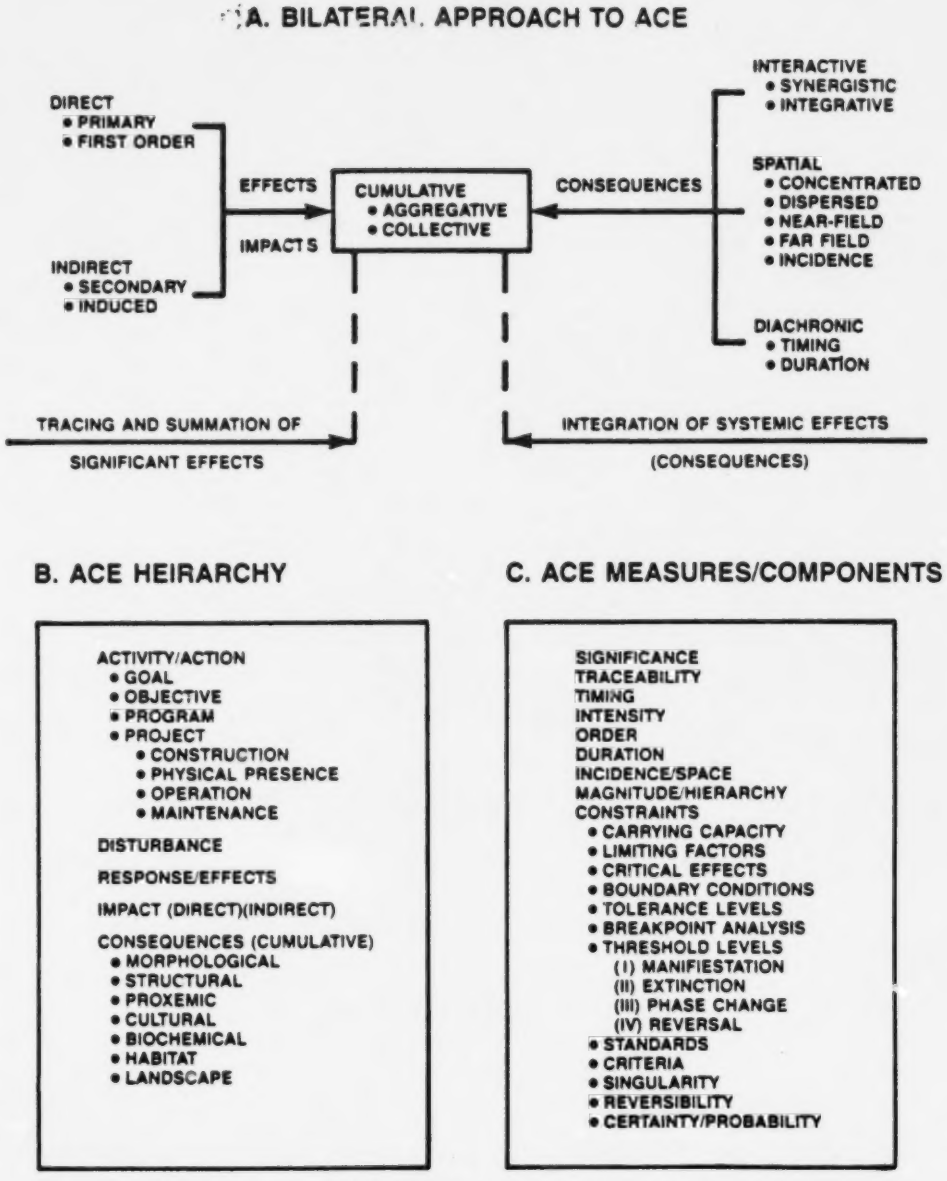

Figure 1. Current considerations for assessment of cumulative effects (ACE).

how commodity credit floors and tax write-offs for farm drainage activities have contributed to the rapid conversion of wetlands and expansion of marginal farmland at the expense of both the individual taxpayer and the environment. Fortunately, these counterproductive measures have recently been reduced or eliminated. Two recent laws, the "swamp buster" provisions of the Food Security Act of 1985 and the tax reform legislation of 1986, have significantly curtailed wetlands conversions. Heimlich and Langner (1986) estimate that as a consequence, no more than approximately 2,000,000 ha (5 million acres) of wetlands, out of approximately 40,000,000 ha (100 million acres) total thought to remain, still have a high or moderate potential for future agricultural conversion.

Complete harmony among government policies seems to be impossible to achieve. For example, what are seen as desirable social goals at one time, and are

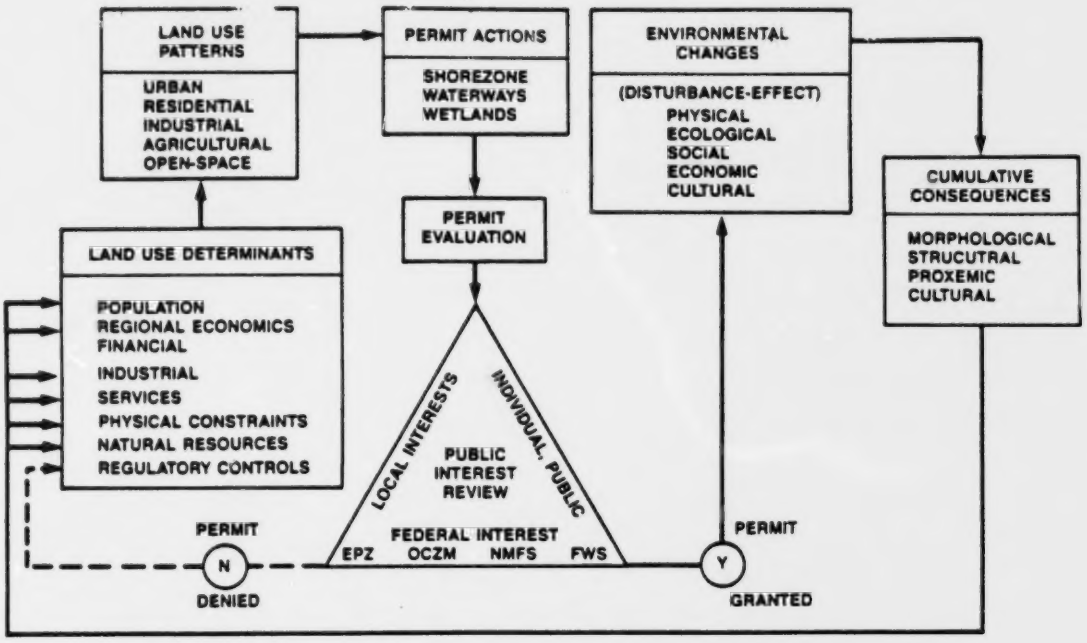

Figure 2. Relationships among land use, regulatory controls, and cumulative consequences.

therefore acted on then, may subsequently be in conflict with later societal goals, and meanwhile may have caused irreparable damage to environmental systems. In another example, regulation necessary to achieve certain societal goals at the same time affects the inherent property rights of individuals (commonly known as the "taking issue"), as well as imposing social inequities. The seeming mismatch in the Corps' regulatory program between the legally exempted wetlands and the regulated ones may exacerbate a situation where the vast majority of beneficiaries of wetlands and aquatic degradation bear no costs, while those living along the edges of the shorezone, waterways, and wetlands bear all the costs, through property use restrictions and federal regulatory controls. The added requirement for CIA may turn out to be the ultimate constraint to growth and development, depending on how it is structured and used in a regulatory context.

What is the most effective and socially acceptable strategy for protecting wetlands, when the OTA report suggests that numerous other federal, state, and local policies and programs have far more influence on wetlands losses than does the Army Corps of Engineers? Should CIA be developed and conducted only for federal regulatory programs, regardless of how little influence on the underlying causes of growth and development they may have? By focusing on a few visible programs with considerable regulatory leverage but comparatively small potential gains, the strategy for wetlands protection may be overlooking far larger and more easily attainable results. It is already evident that the most effective control of wetlands is at the political–programmatic level, as seen by the projected consequences of the new tax reform act and the "swamp buster" act (Heimlich and Langner 1986).

Elements of Cumulative Impact Analysis

Specific land-use patterns emerge as a consequence of a multitude of financial incentives, as well as regional economics and population growth. Land uses and their associated permit actions result in environmental perturbations that cause cumulative environmental effects, which then feed back to the primary determinants of land use and, it is hoped, served as controls to the development and management objectives of an area. Figure 2 provides a schematic overview of this feedback process, filtered through the Corps' regulatory program and public interest review process. (See Section: Regulatory Constraints on CIA, below, for a discussion of this review process.)

The figure indicates that environmental changes can be assessed separately and that they comprise an important input to a more comprehensive cumulative consequence analysis. Further, both the permit action

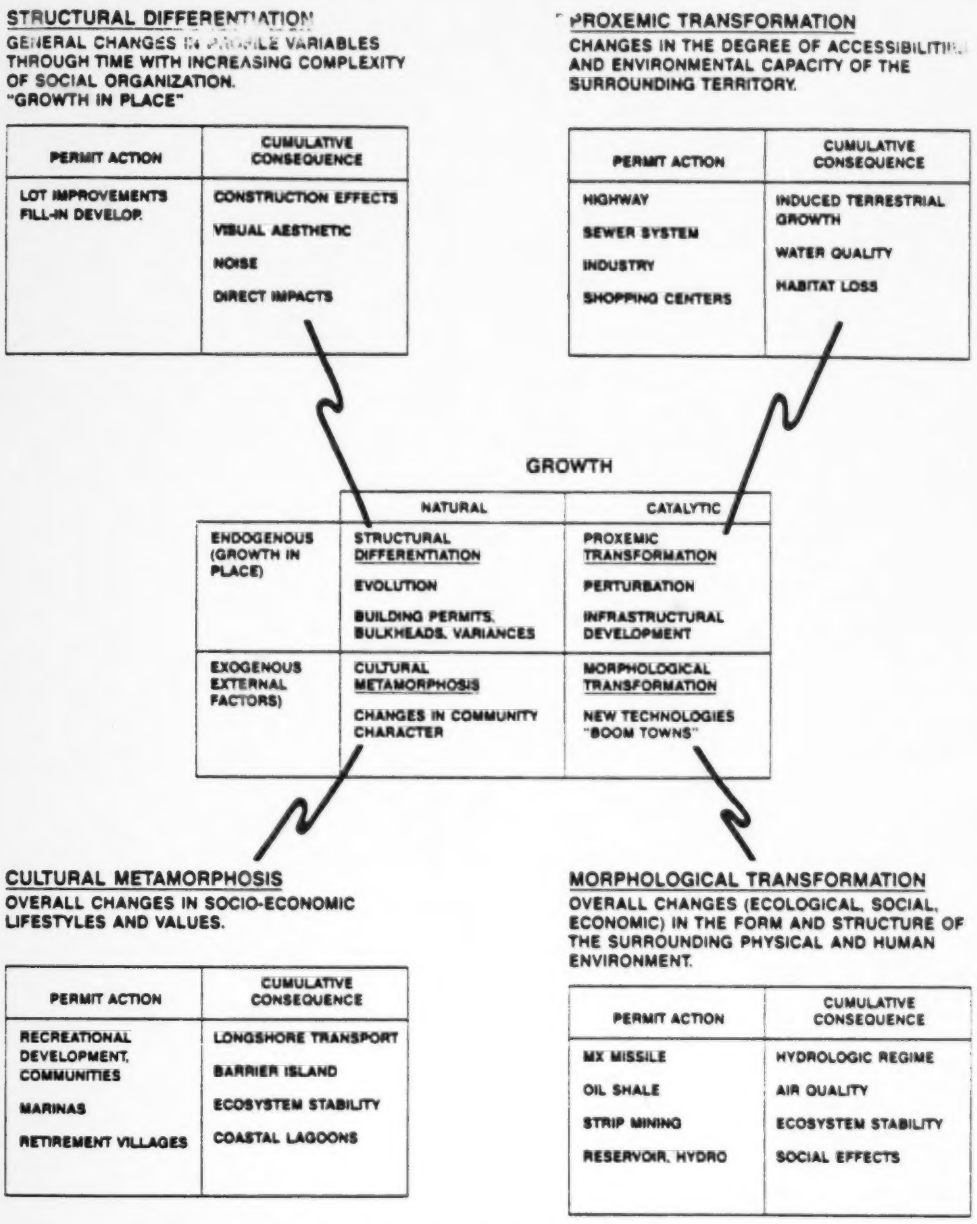

Figure 3. A typology of cumulative consequences of growth and development.

and its environmental effects result in combined physical, social, and psychological changes that Vlachos and Hendricks (1976) have categorized as morphological transformations, structual differentiations, proxemic transformations, and cultural metamorphosis. These terms attempt to reflect the sociocultural perception of development, community stability, whether changes are internal (endogenous) or external (exogenous), and rates of change. It is the level of sociopsychological toleration that ultimately results in changes in perceptions and values connected to growth and development. Figure 3 defines these cumulative consequence terms and presents them within the context of natural and catalytic changes that cause different levels of long-term cumulative consequences. In other words, both the causative agents of change and the

consequences of actions can and should be treated as a part of CIA.

The Corps, however, is limited by law and the nature of regulatory decision making to dealing incrementally with individual permit actions. Thus, the Corps' regulatory program is currently ill-suited to handle the proxemic and morphological transformations caused by externally imposed, catalytic growth factors, altyhough it has experience with internal changes reflecting "growth in place." The Corps' control is limited because a permit is granted for an action or activity that already reflects an ongoing growth pattern that has been directed through local controls and socioeconomic factors. A permit action is a virtual manifestation of an irreversible chain reaction. The local permit evaluation criteria, based to a significant degree on well-defined community values, management objectives, and local culture, can be effectively used, in conjunction with federal criteria, to decide on a particular permit action.

On the other hand, the NEPA definition of cumulative impact, while explicitly recognizing that all significant "... past, present, and reasonably foreseeable future actions ..." can result in cumulative impacts, does not offer any direct guidance for analysis. One must search further to support the distinction portrayed in this article between the narrower function of assessing the cumulative effects of growth and development on a particular environmental resource and the more comprehensive and multiobjective evaluation implied in cumulative impact analysis.

Inherent in the notion of the term *cumulative* is a consideration of the interrelationship of man's past, present, and future actions and the ability of the environment to support such actions. This emphasis on continued productive harmony is evident from the preamble of the National Environmental Policy Act (NEPA), the "Declaration of National Environmental Policy" [Section 101(a)]:

> The Congress recognizing the profound impact of man's activity on the interrelations of all components of the natural environment, particularly the profound influences of population growth, high density urbanization, industrial expansion, resource exploitation and new and expanding technological advances ... declares that it is the continuing policy of the Federal Government, in cooperation with State and local governments, and other concerned public and private organizations, ... to foster and promote the general welfare, to create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the social, economic and other requirements of present and future generations of Americans.

Cumulative impact analysis, then, should not be thought of as a search for an absolute index of negative or positive environmental (i.e., ecological) consequences, but in terms of trade-offs among competing, largely intangible factors comprising the NEPA-defined "human environment." The Corps' own regulations, covering nearly 25 "public interest review" factors, reflects this idea of "balancing" public interest factors that represent generic growth managment objectives. These factors include the explicit consideration of economics, aesthetics, wetlands, fish and wildlife concerns, flood hazards, flood plain values, land use, navigation, shore erosion, water supply, recreation, water quality, energy needs, safety, food and fiber production, and the general welfare of the people. Hence, cumulative impact analysis may be seen as the fundamental evaluation framework for all public interest considerations that are affected by regulatory policies. This view, of course, further complicates CIA, which, in the final analysis, should not be much different than classical multiobjective planning analysis.

In addition to the CEQ regulations that define cumulative impacts, the following CEQ definition of environmental *effects* demonstrates the need to consider an array of growth and development factors.

> *Effects.* (a) Direct effects, which are caused by the action and occur at the same time and place. (b) Indirect effects, which are caused by the action and are later in time or farther removed in distance, but are still reasonably foreseeable. Indirect effects may include growth inducing effects and other effects related to induced changes in the pattern of land use, population density or growth rate, and related effects on air and water and other natural systems, including ecosystems.
>
> Effects and impacts as used in these regulations are synonymous. Effects includes econological (such as the effects on natural resources and on the components, structures, and functioning of affected ecosystems), aesthetic, historic, cultural, economic, social, or health, whether direct, indirect, or cumulative. Effects may also include those resulting from actions which may have both beneficial and detrimental effects, even if on balance the agency believes that the effect will be beneficial [40CFR 1508.8, CEQ 1978].

These definitions further suggest that in some instances highly interactive, nonlinear feedback loops may be separated into what are essentially vector components. Lack of information may make this a pragmatic necessity. As in the case of carrying capacity, which provides a rational boundary for evaluation, the CEQ definition provides a framework for the three vectors: (1) the direct-indirect or traceable cause-effect sequence of impacts; (2) the collective or additive sequence (e.g., acres lost); and (3) the more difficult, interactive, synergistic sequence, which constitutes the core of cumulative impacts (Figure 4). The three vectors of conventionally defined cumulative impact analysis are conveyed within the context of past, present, and reasonably foreseeable actions that affect

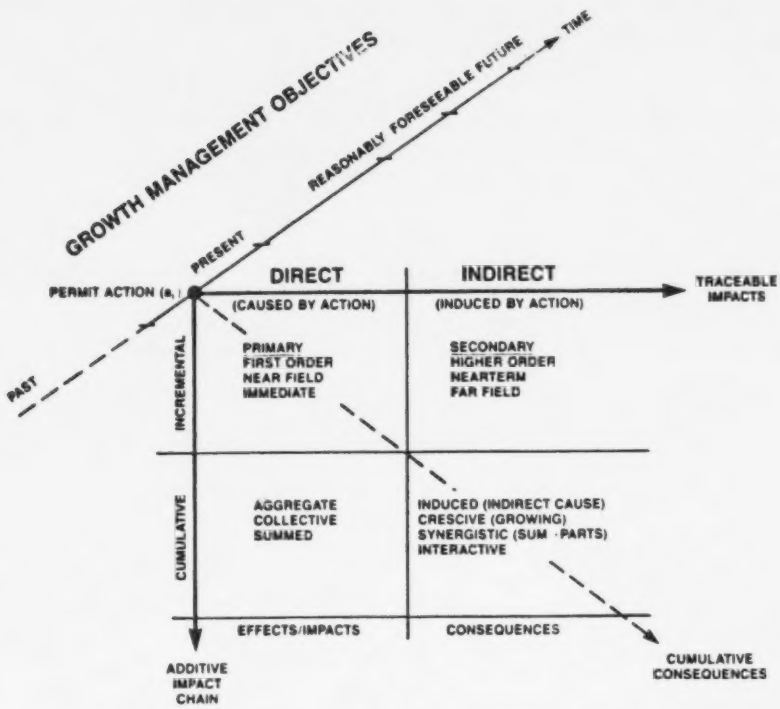

Figure 4. Schematic representation of the Council on Environmental Quality (CEQ) definition of cumulative impact analysis.

the environment. What is missing in this CEQ-based definition, although implicit in the requirement for considering past, present, and future actions, is the development of the rational evaluation system for those actions, i.e., the growth and management objectives of an area.

A regulatory program such as the Corps' permit program for dredge and fill material makes decisions in a procedural (replicative) and incremental (case-by-case) manner, thus contributing to the "nibbling" effect. The procedures are designed to review a private decision from a federal and public viewpoint. As a corollary, the primary focus of evaluation is the largely site-specific permit action (project). Most analysis of direct impacts is focused on habitat-related losses, because conventional ecological analysis has evolved around habitat-based indicator-species correlations (e.g., the US Fish and Wildlife Habitat Evaluation Procedures). All second-order effects (time-crowded, space-crowded, indirect and delayed effects, and synergisms) resulting from interactions with other activities in the area are considered to the degree possible, given the availability of data and methods. The assessment of cumulative ecological effects is limited by lack of agreement on how cascading, cumulative effects of various perturbations at different sites and time periods can be fit into a practical impact accounting framework. As a practical matter, the assessment of cumulative physical and biological impacts is accomplished through a set of constraints or criteria, which form the baseline conditions by which effects are judged. Some constraints are inviolate, such as legally mandated air- or water-quality standards. Others are desired objectives or professionally accepted criteria that can be raised or lowered depending on circumstances and public input, for example, the desirable density for a human or animal population. Together, these physical and biological constraints define the desired *carrying capacity* of an area or a resource. With biophysical carrying capacity, as with other ecological objectives, trade-offs must be made for most environmental management actions; the criteria are not absolute.

Regulatory Constraints on CIA

The much-studied Corps' regulatory program reflects typical but largely unavoidable faults as well as desirable features in a bureaucratic organizational response to environmental regulation. The mandate of the Corps to control dredge- and fill-related activities stems from its responsibility to maintain navigable waterways in the US. The program was never originally envisioned as a wetlands protection program. The Corps is responsible for making decisions in a pro-

gram governed by a group of laws individually administered and nonuniformly interpreted by other agencies, foremost among them the Environmental Protection Agency (EPA), the acknowledged steward of the Clean Water Act (1977). The Fish and Wildlife Service (FWS) and the National Marine Fisheries Service (NMFS) are also major federal actors in this regulatory partnership.

Wetlands protection, exercised through a broad interpretation of Section 404 of the Clean Water Act, has become one of the EPA's top priorities (Hirsch 1988). The other agencies each interpret their mandates for environmental resource protection, including wetlands, in subtly different ways. The debate between the Corps and the EPA over the relevance of Section 404 as a specific wetland-protection provision underscores a large part of the problem—whether evaluation should (1) complement the Corps' "public interest review and balancing" aproach, or (2) focus more narrowly on the assessment of cumulative wetlands effects, or (3) be construed as a series of a priori screening criteria that must be met before balancing social–environmental trade-offs.

Regulatory programs, whether federal, state or local, are designed to provide uniformity of evaluation by considerably limiting bureaucratic discretion. As a result, regulatory evaluation systems largely depend on preestablished screening criteria, standards, accepted professional evaluation conventions, and decision–default criteria. However, no evaluation system that depends entirely on such criteria can successfully react to the diverse situations and complex values that arise in resource use decisions. The quest for programmatic uniformity and decision equity often leads to rigid evaluation and imperfect decisions. The challenge of public policy formulation has always been to design an ideal and flexible evaluation system.

The numerous screening mechanisms employed in a typical regulatory program often reflect a combination of conservative decision thresholds to account for uncertainty, as well as many criteria that represent a minimum acceptable level of resource degradation. Few quantitative evaluation criteria exist for the protection of wetlands, when compared with standards for instream water quality, drinking water, or air polution. Most wetlands protection criteria have evolved in advance of a complete and generally accepted understanding of a wetland as an ecological system and its response to perturbations. This is an understandable decision-making necessity prompted by legislated environmental mandates, e.g., Executive Order 11990. This executive order, like NEPA itself, however, does not require that any particular wetland type be preserved or protected—only that wetlands be considered as a valued ecosystem component based on an assortment of values. It reminds federal agencies that any action contemplated in or affecting wetlands should reflect the social weight given those resources. In other words, the executive order established a guideline or goal for wetlands protection to be factored into consideration of federal actions and programs. Section 404 of the Clean Water Act (1977) imposed a more strictly defined *constraint* related primarily to water-quality degradation of wetlands.

The Corps' regulatory evaluation philosophy tries to compensate, somewhat, for the increasing reliance on constraints as decision criteria through a "public interest review and balancing" approach, a qualitative and largely ad hoc evaluation framework that considers both the purposes of an action and its benefits in terms of area and regional economics, along with social and environmental costs. Power (1979) considers this public interest review process to be "... the major strength in the present regulatory process." Several other analyses of the regulatory program have reached essentially the same conclusion (Haines 1975, Blumm 1980), but the process can be made more uniform and replicable through the use of formal evaluation and decision-making models (e.g., Hollick 1981, Hobbs 1985).

The fact that the Corps is limited by law and the nature of regulatory decision making to piecemeal decisions on individual permit actions is another compelling reason for explicitly factoring growth and development objectives into the formulation of a cumulative impact analysis framework. The Corps' regulatory program largely deals with the growth already in progress. Only in rare instances does it deal with precedent-setting decisions. The final decision, in the form of a permit for a desired project, comes at the endpoint of a long series of numerous decisions about zoning, land uses, and infrastructural investments at the local level that set the context and often provide the impetus for these private actions. The Corps has only limited ability to gude these numerous local decisions through its regulatory program, other than by exercising veto power. Such an action assumes that the specific denial will presumably "serve notice" to local decision makers, inducing them to modify their zoning ordinances. While such a denial is a legitimate tool, the planning and management approach is preferable, especially when dealing with the vague and largely future-oriented analysis inherent in CIA.

Another problem area is the incompatibility of the "public interest review balancing process" with what are essentially private actions. Although the public can

contribute information useful to the permit evaluation process, the regulatory program does not allow them to influence the planning of those individual permit actions. This is especially unfortunate for larger, publicly funded activities such as utilities (water supply, electric, hydropower, sewers), which influence the course of future growth by expanding the base service capacity. The public can only agree or disagree on the impact of what is primarily a private action affecting the public welfare. The regulatory evaluation process essentially forces a "go–no go" choice, and thus decision makers are extremely reluctant to deny permits, especially on the basis of largely qualitative and scientifically tenuous procedures for assessment of cumulative effects. They resort, instead, to a series of modifications to the design, siting, timing, and/or scale of a project in order to mitigate the most unacceptable impacts.

Overall, then, the Corps' existing regulatory program, based on an assortment of legal constraints, evaluation premises, and its position in the decision-making hierarchy, is incongruent with the broad purposes of CIA. The public interest review and balancing process, however, is a rudimentary model that combines many of the necessary components of cumulative impact analysis, without providing the comprehensive scope and uniformity of evaluation that CIA requires.

Wetlands Functions, Attributes, and Values

Semantic confusion surrounds the assessment of wetlands perturbations because of the inappropriate melding of scientific facts about wetland functions and the associated attributes that are valued by society. Wetlands are valued not only for their natural properties that sustain plant and animal species, but also because they serve aesthetic, scientific, cultural, and practical functions important for humans. For example, Executive Orter 11990 lists (Section 5):

a) public health, safety, and welfare, including water supply, quality, recharge and discharge; pollution; flood and storm hazards; and sediment and erosion;
b) maintenance of natural systems, including conservation and long-term productivity of existing flora and fauna, species and habitat diversity and stability, hydrologic utility, fish, wildlife, timber, and food and fiber resources; and
c) other uses of wetlands in the public interest, including recreational, scientific, and cultural uses.

From a purely environmental perspective, the recreational, cultural, aesthetic, and public health and safety values of wetlands are irrelevant. Nixon (1980) has written that the greatest value of a wetland to many may ultimately be its aesthetic attributes. However, "scientific" analysis cannot and should not attempt to measure the intangible attributes of wetlands on a basis commensurate with their physical and ecological properties. Secondary human values are wholly dependent on the primary functions or physical properties that make a wetland what it is, i.e., hydrology, geochemical recycling, and ecosystem support. To that end, the emphasis of EPA (Preston and Bedford 1988) on three primary functions of wetlands: (1) life support, (2) water quality, and (3) flood storage, inappropriately combines the scientists' appraisal of wetlands functions with human-attributed values. This is a situation in which facts (assessment) and values (evaluation) should clearly be differentiated, primarily because they reflect incompatible measurement and analytical systems. The natural function of a wetland is not to prevent floods or to serve as a waste-water treatment facility. It happens that the natural hydrologic and biogeochemical recycling functions may be enhanced to serve human needs, but a trade-off among other competing natural functions is usually involved.

Preston and Bedford (1988) attempt to develop a framework for analyzing the cumulative effects of activities on wetlands that is as rigorous and scientifically valid as possible given the limitations of current knowledge. To that end they develop an assessment framework that relies on traditional scientific reductionism by setting bounds and separating natural processes into discrete functions, which are termed attributes. These attributes inadvertently incorporate a measure of value. Effects that are related to anthropogenic disturbances are then linked to the function–attribute relationship. This system strongly resembles the method for wetlands functional assessment developed by Adamus and Stockwell (1983) for the Federal Highway Administration. This latter method, however, was intended to assign numerical values to wetland functions as a short-cut method and comprehensive evaluation system, reflecting relative wetland values based on comparisons with other weltands and with "ideal" characteristics.

Preston and Bedford wish to improve on this framework by introducing discrete attribute and function measures that capture the dynamic and interactive components of cumulative consequences on wetlands, as well as their effects on the overall ecosystem. Preston and Bedford also broadened the temporal and spatial scales of analysis as recommended by the NRC study (1986), to include contiguous geographic areas or watersheds. In addition, two further steps

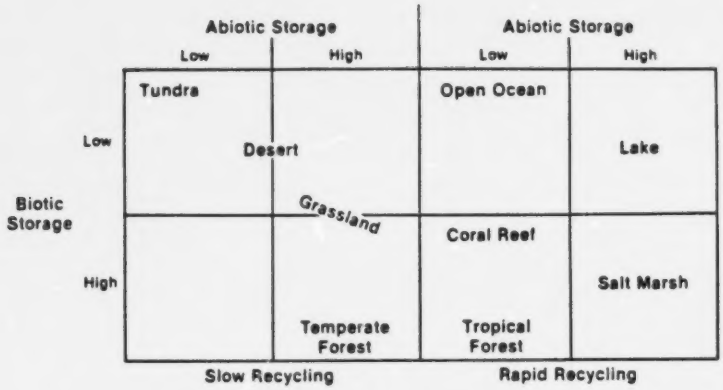

Figure 5. Schematic representation of relationships between macroscopic properties of ecosystem nutrient cycles. This chart can be used to compare the quantifiable storage and recycling attributes of ecosystem, which in turn reveal the relative resistance and resilience qualities of different ecosystem types. (From Webster and others 1975)

need to be taken: (1) the cumulative consequences of interest have to more clearly defined, based on the need by key indicator species for a connected or contiguous variety of wetlands for their survival, and (2) the recent advances and innovations in ecosystem theory need to be reflected more dominantly in the broadening of CIA to encompass wetlands evaluation.

Ecosystem theory is evolving dramatically, judging from the works of Pimm (1982) and O'Neill and others (1986). Many concepts and misconceptions about wetlands and their functions and values have been discussed and dismissed (Nixon 1980). New perspectives are available through the study of landscape ecology (Forman and Godron 1986) and biogeography (Harris 1984). These broader, geography-based evaluation perspectives attempt to go beyond merely additive components and explicitly introduce the interactive habitat needs of species. These needs are reflected in geometric terms such as contiguity and connectivity of wetlands, the spatial distribution of wetlands within an ecosystem, and wetland form, in terms of water surface to plant area ratio.

The landscape ecology approach, however, is merely one part of the cumulative impact analysis puzzle. It resorts to the traditional habitat-based view of the environment. Despite the introduction of additional measures of spatial and temporal species needs, these measures are not especially helpful in gaining insights into the impacts of small-scale hydrologic and/or water-quality perturbations.

A complementary approach developed by Waide (1981) relies on the fundamental principles of ecosystem theory. Waide argues that "concern with the response of wetland ecosystems to outside human interventions is a concern with their stability" and "... until we have a better appreciation of the dominant structural and functional attributes of wetlands viewed as integrated ecosystems, as well as the major biological, physical and chemical determinants of these macroscopic holistic properties, wetland managers will remain generally frustrated in their attempts to predict how wetlands are likely to respond. ..." Waide goes on to construct a macroscopic wetlands/ecology model that centers on two stability vectors, *resistance* to perturbations and displacement, and *resilience* or recovery mechanisms.

Waide refined the stability model of Webster and others (1975) for a range of wetlands. Webster and others showed that resistance was related to large amounts of element storage in either biotic or abiotic form, to long turnover times, and to extensive element recycling. Resilience was related to rapid turnover and recycling rates. Figure 5 shows that a salt marsh is a unique ecosystem because it maximizes biotic and abiotic storage as well as cycling rates, providing the highest stability (high resistance and resilience) of all wetland types. Waide, in a more detailed examination, shows a correlation between the broader ecosystem-level analysis of Figure 5 and the narrower focus on wetland types shown in Figure 6, in terms of the macroscopic properties of ecosystems used to represent the abstract measures of resilience and resistance.

This correlation is not unexpected, however, as wetland systems range from wooded swamps to limnetic or open coastal systems, and therefore show as broad a range as ecosystems in general. Along the ordinate (resistance) axis of Figure 6, measured in terms of total biomass, B (kg C/m^2), the points tend to be separated by almost an order of magnitude as the dominant plant forms change from trees or woody vegetation, to emergent herbaceous angiosperms, to planktonic algae. These changes are associated with differences in water depth and system productivity. The abscissa (resilience) axis, measured in terms of the ratio of net primary productivity, and total biomass, $Pn/B(yr^{-1})$ or turnover rate, represents the dominant

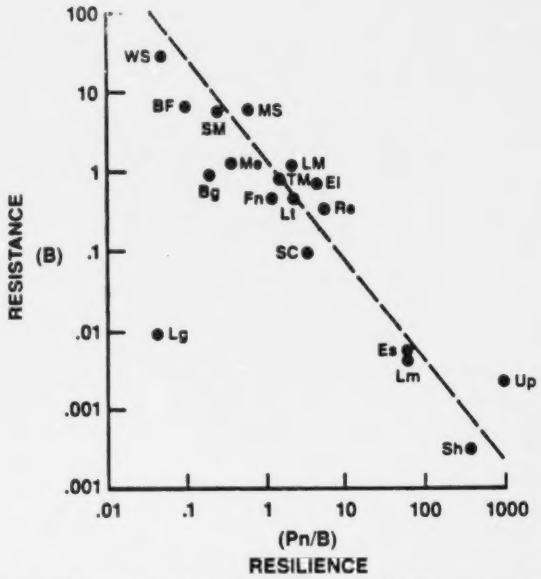

Figure 6. The relationship between wetlands resistance (B = total biomass (kg C/m^2)) and resiliance (turnover rate, P_n = net primary productivity): Ws, wooded swamp; BF, bog forest swamp; SM, salt marsh; MS, mangrove swamp; Me, meadows marsh; LM, lotic marsh; Bg, bog; TM, tidal marsh; Fn, fens; El, estuarine littorial; Lt, littoral; Re, marine reef; SC, streams, creeks; Lg, estuarine lagoon; Es, open estuary; Lm, limnetic; Up, coastal upwelling; Sh, continental shelf. (From Wade 1986)

periodicity in the physicochemical environment associated with the hydroperiod of the system. Thus there is a trend from hydrologically more closed systems at the left to more open hydrologic–oceanic systems at the right of the axis. Note the unique position of coastal lagoons (Lg), which display low resistance and resilience, suggesting an environmental fragility not exhibited by other wetland types. The stability concept indicates what types of perturbations can be absorbed by wetlands or ameliorated by certain management actions, as a check on the piecemeal approach. This clustering of wetlands types is similar to the hierarchical levels of the system of Cowardin and others (1979), which serves as the basis of the US Fish and Wildlife Service wetlands classification and mapping.

In summary, then, the key life- and ecosystem-support function of wetlands can be better understood in terms of comprehensive ecosystem theory. Properties of wetlands can be measured in terms of biotic and abiotic storage, turnover and recycling rates, and hydroperiod. The values of wetlands are human-derived, covering both the natural and anthropocentric functions (recreation, aesthetics, and resource extraction). The Adamus and Stockwell (1983) wetlands evaluation system serves as a good starting point. However, the critical need in assessing cumulative effects of wetlands losses is a better understanding of ecosystem response to perturbation.

Components of an Evaluation Paradigm

Thus far, seven key components of a cumulative impact analysis paradigm have been enumerated:(1) setting planning goals and objectives for future growth and management of an area; (2) developing a scientifically supportable analytical framework for assessing the cumulative effects of various growth and development scenarios; (3) setting goals for wetlands conservation in relation to ecosystem needs; (4) forecasting anticipated growth to assess the resultant demand for services and resources; (5) developing rational analytical bounds for the ecological and social carrying capacity of an area; (6) assessing cumulative effects on a particular set of environmental resources, such as wetlands, which effects are due to the sum of perturbations resulting from different permit actions; and (7) developing a framework for forecasting specific permit actions that characterize different growth and development scenarios.

All of these components need to be linked explicitly. The two most important that need to be tied together are (1) the setting of planning objectives for growth and management with (2) the development of a scientifically supportable analytical framework for assessing the cumulative effects of various growth and development scenarios. Without the ability to test the social, economic, and environmental consequences of these scenarios, it would be difficult to make rational choices or to reformulate assumptions and objectives to reflect the information gained. CIA should not be used solely to identify activities that cause adverse impacts, but more generally to test various trade-offs among objectives, using the information about environmental impacts as a factor in determining the social acceptability of these planning objectives in the face of several possible pathways of long-term environmental deterioration. Furthermore, such information leads to changes in public perception that can stimulate reformulation of planning objectives.

The fundamental point is that the assessment of cumulative impacts on wetlands should not be used simply to set new restrictive criteria but rather to influence the formulation of management and protection objectives. Wetlands are important and valuable resources, as are jobs and economic goods and services. The public ultimately must choose among those objec-

tives, as was stated in the purposes of NEPA and the recent National Research Council report (NRC 1986:2):

> Environmental assessment and management are based on societal goals, which are not always clearly articulated. The social effects of environmental changes and the way goals are developed by society are important aspects of environmental problems.

This view was stated earlier by Beanlands and Duinker (1984:269–270):

> . . . The EIA [environmental impact assessment] should begin with social values playing a dominant role in determining the valued ecosystem components for the assessment. The scoping exercise should solicit the values of both laymen and scientists. Subsequently, scientists are called upon to investigate and predict project-induced changes in the valued ecosystem components. Social values again predominate in making judgments on the importance and acceptability of the predicted impacts.

Subjective public evaluation does not diminish or conflict with the role of scientists in comprehensive analyses of environmental resources. Beanlands and Duinker (1984) and the National Research Council (1986) study on the role of science in environmental problem solving show that there are many avenues for scientific input, and scientists influence or control much of the analytical process and thus the outcomes.

What Beanlands and Duinker (1984) describe reflects the essence of good planning and evaluation theory that has been evolving over the past 50 years in many fields, especially water-resources planning, but has not carried over into EISs or most regulatory programs. For example, the term *valued ecosystem components*, coined by Beanlands and Duinker (1984), has become an operational part of the Environmental Quality Evaluation Procedure (EQEP) of the US Water Resources Council's (1983) principles and guidelines for water resources planning. In the EQEP system, aesthetic and cultural resources (e.g., scenic vistas, historical districts, and archeological sites) can be considered environmental resources on an equal footing with ecological resources. The information derived from the EIS analysis is structured in the EQEP framework so that it can be more easily used to compare future growth and management plans on a common basis.

Evaluation Methods for CIA

There have been several extensive reviews of evaluation methods of assessing wetland values (US Water Resources Council 1981), cumulative impacts (US Army Corps of Engineers, Institute for Water Resources 1981, Horak and others 1983), and environmental impact analysis (Hollick 1981, Nichols and Hyman 1982, Hobbs 1985). There has also been a study evaluating a particular CIA approach developed for the Corps (Contant and Ortolano 1985). None of the reviews explain the wide disparity among methods, nor do they form a basis for choosing one evaluation system or one model over another. As a result, different approaches are treated as equally valid, even though the procedures and models reflect substantially different theoretical premises and evaluation philosophies.

Cumulative impact analysis is, by definition and by virtue of its purposes, a complex analytical task that requires many methods and models within a uniform evaluation framework. The purpose of CIA is reflected in the structure of the evaluation framework, which then defines the analytical methods and evaluation procedures needed. However, it is also important to consider the efficacy of the environmental impact statement (EIS), which is the existing evaluation framework most likely to be used for CIA. The EIS reflects a particular evaluation perspective through its procedures (CEQ 1978), but it also has a number of deficiencies. These deficiencies include the absence of a uniform evaluation perspective, absence of a common basis for comparing impacts (i.e., "baseline" condition; comparison of effects "with" and "without" an action), no commonly accepted decision rules for determining a significant adverse impact, and absence of an acceptable system for balancing intangible and incommensurable environmental values, or even for balancing beneficial and adverse impacts.

Most of the EIS deficiencies reflect inadequate assessment techniques. There are also deficiencies in the evaluation philosophy of the NEPA process, but few articles address this. Knetsch and Freeman (1978), McAllister (1980), Ortolano (1984), and Stakhiv (1986, 1987) have shown that, even with the best of models and methods, the EIS cannot provide consistent results because there is neither a uniform evaluation framework nor accepted rules for determining significant impacts, or even what comprises irreversible commitments of resources. Notwithstanding a large contribution of scientific facts and sound ecological theory, to many analysts the development of the EIS as an evaluation document is an art, dictated by convention and procedure. An issue that must be resolved is whether CIA will follow the lines of conventional EIS analysis, which would substantially circumscribe its usefulness, or be the broader evaluation–decision framework intended by NEPA.

The neglect of NEPA policies and their relationship to evaluating public or private actions exists because

the most widely read and analyzed aspects of NEPA were the action-forcing provisions of the policy, i.e., Section 102(2)(c), which institutionalized environmental impact analysis by requiring preparation of environmental impact statements, a consequence of the immediate legal attention given to EIS provisions and rigorous enforcement by the courts. Naturally, then, attention was devoted to procedure rather than substance. With time, a skewed form of impact analysis evolved that was neither scientific nor helpful to the main purpose of the EIS. "The EIS was indeed action forcing, but the action to be forced was described elsewhere in NEPA, a fact often lost on many who somehow saw the EIS as an end in itself and NEPA essentially as a procedural act. The EIS requirement could only be understood and appropriately implemented if interpreted in the context of the rest of NEPA . . ." (NSF 1979:6).

This broader view of the EIS is particularly relevant to cumulative impact analysis, which is a much more comprehensive and far-reaching extension of conventional, site-specific environmental analysis. Congress did not necessarily . . . "intend to prohibit federal agencies from making decisions that had adverse environmental consequences. Instead, Congress required a balancing of effects and considerations" (Ortolano 1984). Section 102(2)(b) of NEPA states that:

> . . . all agencies of the Federal government shall identify and develop methods and procedures, in consultation with the Council on Environmental Quality . . . which will insure that presently unquantified environmental amenities and values may be given *appropriate consideration* in decision-making along with economic and technical considerations . . . [emphasis added].

The major problem is that despite many references to balancing social, economic, and enviromental objectives within NEPA itself (e.g., giving "appropriate consideration"), there is ". . . no requirement to reconcile or even detail environmental–economic trade-offs . . . made for each alternative project" in the EIS (Knetsch and Freeman 1979).

Since a uniform evaluation perspective is not offered within the NEPA procedural guidelines for EIS analysis, individual project and program alternatives are often examined under different sets of evaluation permises within the same report. Without consistent evaluation criteria, similar to benefit–cost accounting in the principles and guidelines (P&G) or environmental accounting in the environmental quality procedures of the P&G, evaluation procedures may be inconsistent for different impacts within an EIS and between the EIS and the original regulatory or planning decision document. This is particularly true when several different agencies independently contribute significant portions of the EIS analysis.

Existing methods or approaches that may potentially fulfill the conditions set for CIA generally fall into four distinct categories: (1) subjective numerical measurement criteria and guidelines for direct evaluation of effects and impacts; (2) methods that link deterministic, analytically based models with more subjective simulation models and attempt to contrast desired goals with actual outcomes; (3) unified, holistic theoretical approaches, reflecting a single evaluation perspective; and (4) prescribed land use approaches that directly translate management objectives into environmental use constraints.

Valuation methods and models. These are static evaluation systems that assign qualitative or numerical values to a predetermined set of features. They attempt to combine physical and ecological criteria with a static or prescribed social valuation system. The best known forerunner of all subjective, numerical rating methods is the Leopold and others (1971) impact matrix. The Reppert and others (1979) wetlands rating approach, the Adamus and Stockwell (1983) wetlands evaluation method, the Dee and others (1977) environmental evaluation system, and the recently developed CIA system for evaluating the environmental effects of multiple human developments (Bain and others 1986) and multiple hydropower developments (Emery 1986) are all examples of such an approach.

Linked deterministic and simulation models. Oriented towards a mass balance or input–output techniques, this approach links a number of different types of models reflecting the physical (hydrologic models, water-quality models) and/or ecological systems with econometric models to test the acceptability of policy and/or management actions. The strategic environmental assessment system (SEAS) was initiated by EPA in an attempt to model the environmental carrying capacity of the United States (House and Williams 1971), and for obvious reasons was never completed (House 1976). Another comprehensive systems analysis approach to cumulative impact analysis was attempted by the New England River Basins Commission (1978) for the Connecticut River, but never completed. An excellent study, which encompasses many of the principles espoused in this paper, was completed for Lake Tahoe (Gilliland and Clark 1981). Isaard and others (1972) early model of economic–ecological linkages for a coastal bay and wetland system was rigorously developed conceptually but fell short through lack of ecological data and inadequate ecological theory.

Unified, holistic theoretical approaches. These approaches rely on a dominant conceptual perspective

such as energetics (e.g., Odum and Odum 1976, US Army Corps of Engineers, Institute for Water Resources 1977), econometrics (Luken 1976), or resource economics (Boland 1983, Farber and Costanza 1987, Stavins 1987). Luken's econometric approach assesses how much wetlands area would be required in the future by each economic sector in the San Francisco Bay Area. Another example of a pure economics-based approach, relying on the premise that permits are a market phenomenon that impose externalities, was a study done by Maloney and others (1977) for South Carolina's regulatory program. Similar economic analyses have been conducted by Batie and Mabbs-Zeno (1985) for perserving wetlands and by Bell and Leeworthy (1987) for establishing the trade-offs between marinas and wetlands preservation.

Land use designation approaches. These approaches rely on a predetermined designation of resource-compatible uses. They reflect a regulatory or land-use zoning approach based largely on a direct translation of public values and environmental objectives into land-use restrictions. Simply stated, various natural areas are classified as development compatible; as conservation zones, where only certain activities are compatible with the existing altered environment; or as preservation areas where only a few recreation and resource-extraction activites are allowed, with the idea that such restrictions are desired by the public. The Corps made a number of such wetlands designations in the 1970s in Oregon and has since returned to the concept, along with EPA, under the term special area management plans (SAMPs). The idea behind this appealingly simple approach is that local citizens must choose their destiny consistent with environmental protection objectives. Such an approach fulfills a major initial condition of CIA philosophy espoused in this paper. Designations of this kind provide the permit processor with a set of consistent and context-specific guidelines and explicit objectives for growth, development, and environmental protection. A large number of computerized mapping and overlay systems exist for supporting such an approach analytically, including a variety of land-use forecasting models.

A well-structured SAMP approach to managing bottomland hardwood forests was developed through a series of EPA-sponsored workshops (Gosselink and Lee 1987:100). Although somewhat less comprehensive, it meets most of the conditions for CIA set forth in this paper. The authors correctly state that ". . . goal setting is the heart of cumulative impact assessment. Without it . . . the demonstration that severe cumulative impacts have occurred on a watershed cannot lead to judicious management." The authors include technically supported goals related to resource conservation and social goals related to the local political and social setting. Technical goals are the scientifically derived objectives for wetlands maintenance. The social goals, however, were to be related only to conservation potential. Economic growth objectives and development could be considered only to the extent that they were compatible with the overall orientation towards conservation. Appropriate social goals were defined as amenity values (hunting, recreation, aesthetics), educational values, and management considerations. This unfortunate and unacceptable restriction, in terms of good planning theory, left out the valid and necessary considerations of regional economic growth that are a vital part of CIA.

Heuristic Model of CIA for Wetlands Permits

The Model

Many different approaches to CIA have been discussed. Each has it strengths and weaknesses. None is ideal, nor is a comprehensive, rational analytical system likely to be available in the near future, given the numerous gaps in our knowledge of ecosystem theory, economic forecasts, and environmental trends.

The ideal CIA model must assess the interactions and feedback mechanisms between growth and environmental consequences, an assessment that stems both from the original purposes of NEPA and from sound public-choice theory. Setting a priori growth constraints and environmental resource use standards through a series of disjointed regulatory decisions violates the democratic basis of public choice and is an inefficient way of managing public resources.

A simple heuristic mathematical model is constructed to highlight and quantitatively demonstrate the essential ingredients of cumulative impact analysis discussed in this paper. The model abstracts and idealizes goals, physical constraints, decision objectives, and interactions between human activities and the environment. The model allows one to assess directly cumulative environmental effects and appraise their impacts on the human environment. This model uses a linear programming approach. Cumulative impact analysis, as viewed here, requires that we integrate several levels of analysis with different sets of information: (1) a set of development–conservation goals against which alternative actions and policies may be evaluated; (2) a set of forecasts of expected growth and development scenarios that attempt to fulfill the desired goals; (3) a set of biophysical wetlands con-

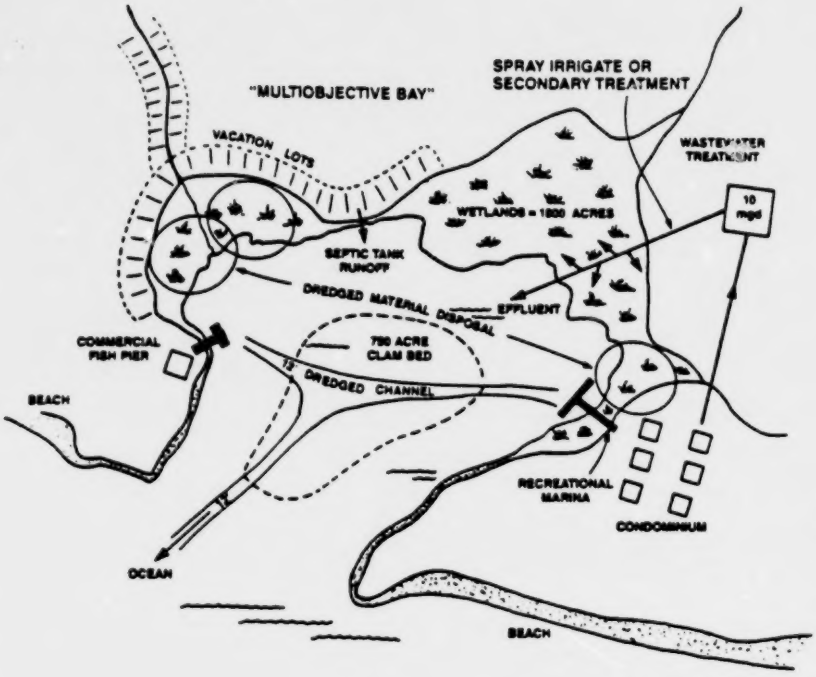

Figure 7. A hypothetical growth scenario in Multiobjective Bay, requiring a series of permit decisions. Multiobjective Bay is a hypothetical ocean-bay area that is subject to rapid recreational and commercial development.

straints operating within a developed theory or model of ecosystem response to natural and human perturbations; and (4) a set of environmental protection standards and criteria that serve as minimal constraints, defining acceptable carrying capacity, within which a comprehensive assessment of impacts on an area can be made.

The model applies linear programming techniques and algorithms that were adapted from a similar approach by Hill (1977) and based on the earlier work of Isaard and others (1972) linking economic–ecologic impacts through input–output analysis. A model such as this, which uses mass balance equations, may be useful in helping to understand economic–ecologic linkages, to evaluate trade-offs between private financial decisions and the public interest, and to analyze the effects of incremental decisions on the physical carrying capacity of an area. The model also abstracts a few key aspects of the Corps' public interest review process. The two underlying elements in such a model are: (1) the available resources, together with constraints, representing the carrying capacity; and (2) the choices for development (or preservation), reflecting the planning objectives.

An Example

The model will be demonstrated by devising a scenario for gradual development of an estuarine bay–wetlands system, Multiobjective Bay (Figure 7). Multiobjective Bay is simply a hypothetical ocean-bay area that is undergoing rapid recreational and commercial development. There are any number of growth and management objectives that can be specified and reflected through a series of measures of economic growth, tax revenue, or loss of wetland acres. Actual patterns of growth can be compared to the possible optimal levels as a way of refining objectives and constraints.

For Multiobjective Bay, these are the parameters used in the model:

1) Available resources:

a.	Spartina wetlands	≤1800 acres
b.	Clam beds	≤750 acres
c.	Dissolved oxygen deficit	≤3.25 ppm
d.	Nitrogen assimilation	≤9,000 lb/yr
e.	Detritus production	≥consumption/yr
f.	Algae/phytoplankton production	≤100,000 lb/yr
g.	Fish catch	≤50,000 lb/yr

Note: metric conversion factors: 1 acre = 0.4047 ha; 1 lb = 0.4536; 1 million gallons per day (mgd) = 0.0438 m^3/sec.

2. Choices for development or preservation (choice variables):
   a. Fill/preserve Spartina (marina,

commercial fishing, vacation lots, condominium, spray irrigation	≤1800 acres
b. Build waste-water treatment plant (if condo is built)	≤10 mgd
c. Build vacation lots (incl. bulkheads, filling, septic tanks)	≤200 lots
d. Build retirement/recreation condominium complex (with marina)	≤1
e. Build recreational marina (with or without condo)	≤2
f. Build commercial fishing marina	≤1
g. Harvest clams	≤750 acres
h. Commercial fising	≤50,000 lb/yr

Note: metric conversion factors: 1 acre = 0.4047 ha; 1 lb = 0.4536 kg; 1 million gallons per day (mgd) = 0.0438 m^3/sec.

A series of mathematically specified mass-balance equations are constructed for each potential resource use, linking all the possible activities or choice variables with the affected resources. The linkages are made through coefficients or parameters that reflect exchange rates that represent the use of a given resource by an activity (e.g., each vacation lot requires one quarter of an acre of Spartina wetland). A single objective is then selected to show how the attainment of various levels of that objective (e.g., economic benefits of development) is affected by other desired activities and environmental constraints. Different objectives, reflecting environmental protection goals, regional development, or species enhancement can be alternatively tested to understand the nature of the most useful pattern of growth and development for a particular area.

The difficulties of constructing such a mathematical model include: (1) constructing a model or abstracting "real world" situations reflecting all the important interactions between resources and uses; (2) representing qualitative aspects of interactions that reflect existing social values and concepts such as stability, resilience, and resistance; and (3) determining the "exchange rates" or parameters. The third problem may be the most difficult. After all, if the data were available, deterministic solutions and environmental impact analysis would be relatively simple. Virtually the same information is needed for traditional direct/indirect–cause/effect impact analysis.

An example of the difficulties, in what is admittedly a highly simplified wetlands-permit model, is the problem of quantifying organic detritus and its role in the ecosystem as well as its economic value. The production of detritus, i.e., the by-products of organic decay of leaf material, is a key value of wetlands to the estuarine food chain. The scientific literature does not adequately specify the annual production of detritus by wetlands or of its assimilation and use by various species through the food chain. As a result, the exchange rates used in this model were abstracted from various literature sources or were based on reasonable assumptions.

The mass balance equation approach is illustrated for detritus production and consumption; its uses the following variables:

X_1: Preserve Spartina (PSPAR): produces (+) 4000 lb/acre/yr

X_2: Fill Spartina (FILL): produces (+) 100 lb/acre/yr

X_3: Spartina used for filtering secondary wastewater (FILT): produces (+) 6000 lb/acre/yr

X_4: Recreational marina (RMAR): produces (+) 500 lb/acre/yr

X_5: Commercial fishing marina (CMAR): produces (+) 1000 lb/acre/yr

X_6: Fish Catch (FISH): consumes (−) 100 lb/lb of fish/yr
(note: some fish consume detritus indirectly through food chain)

X_7: Condominium (CONDO): produces (+) 500 lb/acre/yr

X_8: Vacation lots (VAC): produce (+) 500 lb/lot/yr

X_9: Secondary treatment plant (SECT): produces (+) 30,000 lb/mgd/yr

X_{10}: Clam bed (CLAMB): consumes (−) 30,000 lb/acre/yr

X_{11}: Algae (ALGA): produce (+) 1 lb/lb algae/yr

The mass balance equation specifies that the sum of detritus production and consumption ≥0:

$$+4000\,X_1 + 100\,X_2 + 6000\,X_3 + 500\,X_4 + 1000\,X_5 + 500\,X_7 + 500\,X_8 + 30{,}000\,X_9 + X_{11} - 100\,X_6 - 30{,}000\,X_{10} \geq 0$$

All such mass balance equations are arrayed in an input–output matrix.

A drawback in this kind of artificial analysis is that a growth-inducing wastewater treatment plant may be spuriously put on line solely to produce detritus required by fish and clams. If constraints are set incorrectly or too rigidly, such decisions may be indicated regardless of cost, leading to a socially irrational choice.

The real value of this model is that it can generate combinations of solutions and help to choose among alternatives on the basis of specified decision rules

(e.g., maximize annual income or minimize dissolved oxygen deficit). The choice may be between wastewater treatment by conventional secondary treatment processes (with a cost of $75,000/mgd, yielding 30,000 lbs of detritus annually in the effluent) or through spray irrigation of the primary treated wastewater onto the Spartina wetlands. Spray irrigation has the positive value of maintaining the Spartina wetlands relatively intact, i.e., preserving them, but also precludes other values (hunting, aesthetic, etc.). For this example, the spraying application rate was estimated to be about 0.05 mgd/acre. Therefore 10 mgd of spray irrigation would require 200 acres of Spartina. Each spray-irrigated acre, however, would add to the nutrient of loading of the bay, increasing naturally produced nitrogen (N) from 5 lb/acre/yr to 13 lb/acre/yr. This fertilization effect would increase Spartina biomass production, resulting in an increase in annual detritus production of 2000 lb/acre (the difference between natural Spartina production of 4000 lb/acre/yr, and Spartina with spray wastewater filtering at 6000 lb/acre/yr).

Thus, the total additional maximum production of detritus through spray irrigation of 10 mgd of wastewater would be 200 acres × 2000 lb/acre = 400,000 lb. This is 100,000 lb more than would be produced through simple secondary treatment of wastewater (20 mgd × 30,000 lb detritus/mgd = 300,000 lb). The additional detritus can support a larger fish stock and clam stock, making commercial marina development, for example, an economically viable activity.

There are, however, other system constraints on unfettered economic development of the bay's resources. Key among these is the oxygen demand of each activity and the nitrogen input. Oxygen deficit or dissolved oxygen (DO) availability is one of the few parameters for which there are natural physical limits [0–7.25 ppm (saturation) at 20°C]. The accepted minimum for maintaining aquatic ecological values is 4 ppm, leaving an "allowable deficit" of 3.25 ppm. Detritus production and consumption are also associated with dissolved oxygen and nitrogen levels for each activity. In this optimization model, each mass balance equation is considered independently, and the interaction of each mass balance relationship and the mutually imposed constraints are calculated simultaneously. Spraying wastewater onto wetlands may be beneficial from a wetlands conservation and fisheries standpoint, but it may result in higher oxygen consumption overall and/or nitrogen fertilization, leading to the eventual eutrophication of the bay. There may also be other activities with fewer harmful ecological impacts that generate greater economic benefits.

In this model economic benefits are optimized subject to natural physical and resource constraints. For an objective function, e.g., the maximization of annual income, each activity is assigned a net annual return. However, the optimum economic solution may be traded-off for predetermined levels of acceptable constraints; for example, the dissolved oxygen deficit constraint may be increased to a more stringent standard of ≤2.5 ppm.

Table 2 summarizes the results of some of the iterations on varying the DO-deficit constraint. For example, for a DO deficit of 3.25 ppm, row 10 of Table 2 shows that $596,660 of annual income is generated through a combination of the following activities: (1) filling of 113 acres of Spartina (out of a maximum of 1800); (2) building one commercial marina and one recreational marina, which allows 50,000 lb of fish to be caught and 60 acres of calm beds to be harvested; (3) spray irrigation of 5.72 acres of Spartina; (4) building 86 bay frontage vacation lots; and (5) production of 706 lb of algae.

Since a DO-deficit standard of 2.5 ppm is more stringent, we would expect the optimization routine to reduce the level of some activities or change the combination of activities. Row 13 of Table 2 shows the reduction in the sale or number of activities from row 10, although all the activities are the same. The primary change is a reduction of vacation lots from 86 to 46 resulting in 20 fewer acres of Spartina filled in (0.5 acre/lot), less wastewater generated, and less nitrogen fertilization, leading to a lower algal standing crop and a lower eutrophication potential. A condominium is the economically preferred solution only when the DO deficit is raised to 4 ppm (roughly equivalent to a DO standard of 3 ppm, the summer minimum for aquatic life). The condominium is associated with the 5 mgd secondary treatment plant, which doubles the algal crop through increased nitrogen output. The simple DO deficit–net economic benefit trade-off is shown in Figure 8. This figure clearly shows that requiring a very stringent standard of dissolved oxygen deficit (≤1.5 ppm) will exact a severe cost to the regional economy. Thereafter, the increase in economic gains is incrementally small for each increment of increased DO deficit.

The purpose of simulation modeling is to learn about the best overall development strategy through sensitivity analysis and variation of assumptions. In general, the modeling seems to show that there are different, distinct clusters of acceptable growth patterns. If the model is realistically constructed, the choices lead to stepwise, discontinuous optima, as different combinations of desired objectives are matched together.

In such a formulation, objectives may be posed as

Table 2. Summary of results: maximizing net annual income for various dissolved oxygen deficit constraints in multiobjective bay.

Run	Constraint DO deficit (ppa)	Objective Income ($)	Choice variables[a] fill (ac.)	cmar #	cond #	sect (MGD)	filt (ac.)	rmar #	fish (lb.)	vac #	clam (ac.)	algae (lb.)
1	7.00	809,963	206.5	1	1	5	7.46	1	50,000	173	55	2197
2	6.00	753,272	180.0	1	1	5	6.40	1	50,000	120	57	1989
3	5.50	724,393	167.0	1	1	5	5.86	1	50,000	92	58	1884
4	5.00	696,582	153.0	1	1	5	5.34	1	50,000	67	60	1782
5	4.50	667,702	140.0	1	1	5	4.80	1	50,000	40	61	1676
6	4.25	653,797	133.5	1	1	5	4.54	1	50,000	27	61	1624
7	4.00	639,892	127.0	1	1	5	4.28	1	50,000	14	62	1573
8	3.75	625,360	126.5	1	0	0	6.26	1	50,000	113	59	811
9	3.50	610,505	119.0	1	0	0	5.98	1	50,000	99	60	757
10	3.25	596,600	113.0	1	0	0	5.72	1	50,000	86	60	706
11	3.00	582,695	106.5	1	0	0	5.46	1	50,000	73	61	655
12	2.75	567,720	99.5	1	0	0	5.18	1	50,000	59	62	600
13	2.50	553,815	93.0	1	0	0	4.92	1	50,000	46	62	549
14	2.25	539,910	86.5	1	0	0	4.66	1	50,000	33	63	498
15	2.00	526,004	80.0	1	0	0	4.40	1	50,000	20	63	447
16	1.75	511,030	73.0	1	0	0	4.12	1	50,000	6	64	393
17	1.50	455,709	46.0	1	0	0	2.24	0	30,000	12	134	259
18	1.25	431,100	40.0	1	0	0	2.00	0	30,000	0	123	212
19	1.00	274,961	31.0	0	0	0	2.04	1	20,000	2	50	165
20	0.50	98,194	3.5	0	0	0	0.14	0	0	7	0	27

[a]Legend: fill, filling of spartina marsh by various activities (acres); cmar, commercial marina, # units built; cond, condominium, # units built; sect, secondary wastewater treatment plant (million gal/day); filt, filtration of wastewater by spray irrigating spartina marsh; rmar, recreational marina, # units built; fish, fish catch from commercial, recreational marina; vac, vacation homes, # units built; clam, clam bed, acres harvested annually; algae, algae amount, used as eutrophication indicator. Metric conversion: 1 mgd = 0.0438 m^3/sec; 1 acre = 0.4047 ha; 1 lb = 0.4536 kg.

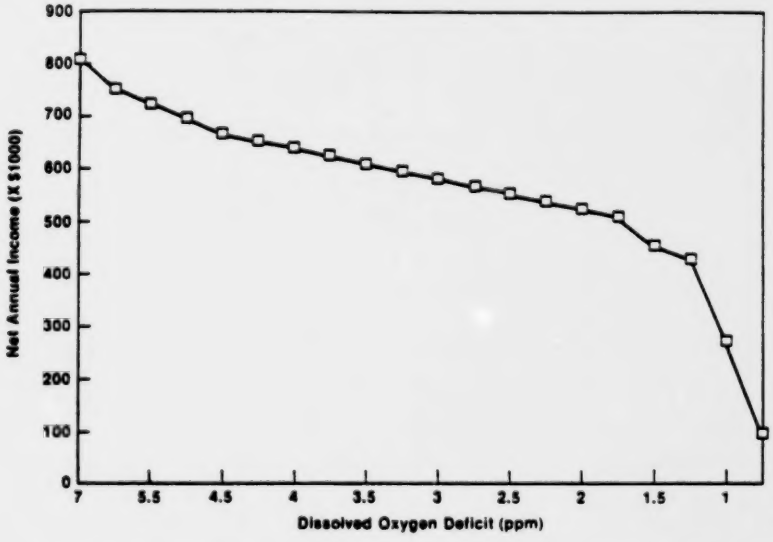

Figure 8. A trade-off curve for economic activity (net annual income) and dissolved oxygen deficit in Multiobjective Bay.

constraints and vice versa. If net economic benefit is the primary objective, then the DO-deficit constraint may be varied to explore how best to achieve this end. Conversely, dissolved oxygen may be maximized subject to an economic constraint in order to reflect minimum acceptable regional income or local tax revenue.

Net economic income is a useful albeit abstract measure of economic well-being. A more politically useful measure of growth is the tax base that is generated from alternative patterns of development. Therefore, a comparison or trade-off between the regional economic development objective of maximizing net in-

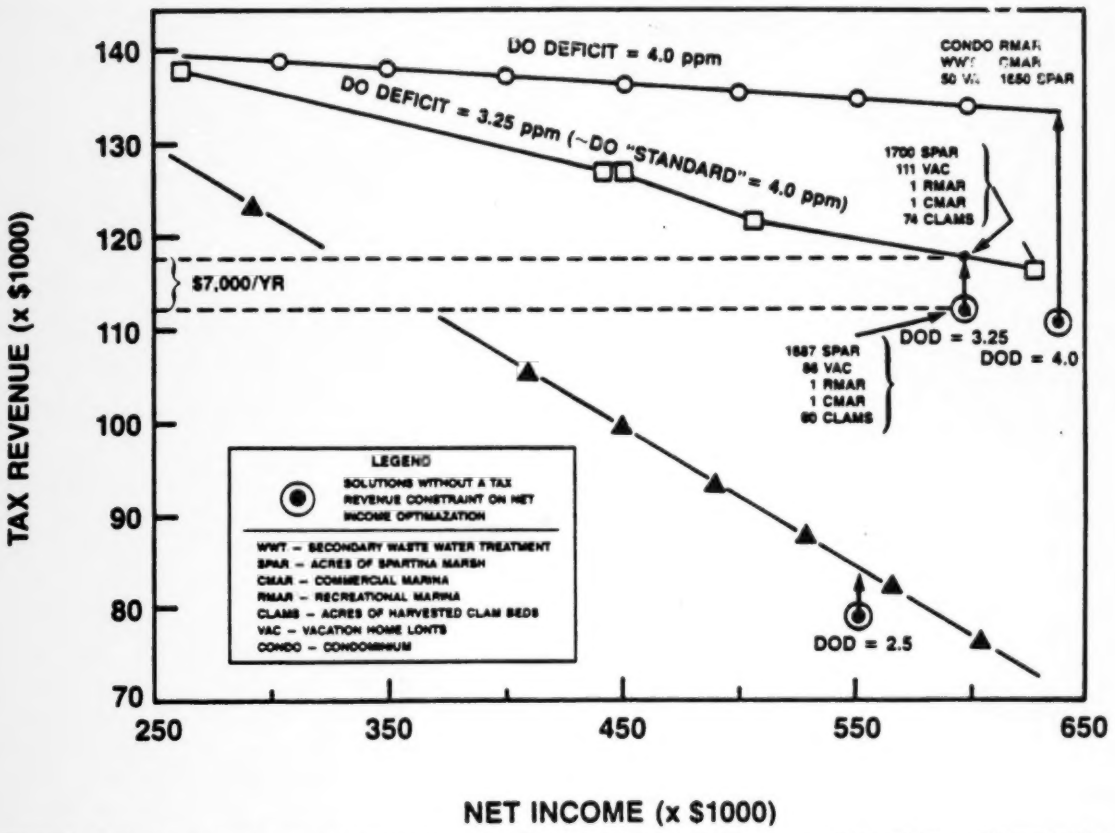

Figure 9. Regional net income versus local tax revenue tradeoffs for three dissolved oxygen deficit (DOD) conditions in Multiobjective Bay.

come and the more political objective of maximizing tax revenues should reflect one of the more realistic choices that are typically made in local land-use decisions.

Further use of the model is illustrated for these economic benefits/constraints. First a series of solutions was generated without a tax revenue objective, optimizing only net income (Figure 9). Three solutions are shown as partially filled circles for each of the target dissolved oxygen deficit constraints. Subsequently, a full set of trade-off curves was generated, optimizing tax revenues while showing resultant net income for each combination of activities at each of the DO-deficit targets. What the trade-off curves show is that, without exception, introduction of an explicit tax-revenue maximization objective gained more tax revenue without sacrificing net income. For example, for the same net annual income of $600,000 and at DO-deficit constraint of 3.25 ppm, tax revenue increased $7,000/yr by shifting development away from condominium development to more vacation homes. This also used up fewer acres of Spartina. The new solution shows that vacation homes maximized both tax revenue and regional income when compared to condominiums. The two solutions had the same water quality impacts, although not necessarily the same ecological impacts.

Even this simple model may provide a number of insights. For example, spray irrigating a wetland with partially treated wastewater may appear to be a good conservation–preservation alternative. In this instance, however, even though spray irrigation is cost effective when compared to the direct costs of a secondary wastewater treatment plant, the model produces a higher dissolved oxygen deficit in the bay and higher nitrogen fertilization, further hastening eutrophication. These and other unintended consequences of narrowly defined objectives and restrictive measurement criteria can be identified through this analytical approach to cumulative impact analysis.

The Value of the Model

A model such as this that accurately reflects economic–ecological interactions could obviously assist

the "public interest balancing" requirements of the Corps' regulatory program, as well as that of cumulative impact analysis. Cumulative impact analysis is handled implicitly in three distinct ways by such a model: (1) Each added activity can be examined by varying the parameters, and its effects on the basic physical constraints and the objective function (e.g., maximize economic benefits) can be traced. (2) The effects of several different streams of desirable future activities on the constraints (or carrying capacity) can be examined. (3) Different combinations of objectives, weighted by public preferences, may be examined to develop an overall set of desirable growth and development goals.

Most important, perhaps, is the sensitivity analysis that decision makers may engage in with such a model at their disposal. Trade-offs among objectives can be examined when we know how individual resources affect the entire spectrum of future development. The formulation of the evaluation model itself is probably the single most important action in the analysis. Such models impose a higher level of analytical rigor, leading to better informed decision making.

In summary, a case has been made that cumulative impact analysis cannot simply be thought of as an extension of conventional impact analysis, with its emphasis on process and procedure. Furthermore, CIA should not be confined solely to the ecological impacts of human activities. Neither can the cumulative consequences of a single action or project be isolated from the social, economic, and environmental goals that comprise the attainment of a desired state of the human environment. Cumulative impact analysis is viewed as the requisite evaluation framework for its correlate, comprehensive planning. Since the Corps' regulatory program responds to activities that have already been subjected to planning constraints at the local level, and the permits represent a piecemeal decision-making process, cumulative impact analysis for single permits may be an incongruous undertaking. A heuristic model is presented to demonstrate how CIA may be conducted within a regulatory program for general or regional permits.

Acknowledgments

This article was greatly enhanced by the valuable critical review of Dr. Barbara Bedford of Cornell University and the thorough review, commentary and superb editing of Mr. David Gooding, editor for the Ecological Society of America and Ms. Dooley Kiefer of Cornell University.

Literature Cited

Adamus, P. R., and L. T. Stockwell. 1983. A method for wetland functional assessment, vol. I. Critical review and evaluation concepts. US Department of Transportation, Federal Highway Administration Report No. FHWA-IP-82-23. National Technical Information Service, Springfield, Virginia, 176 pp.

Bain, M. B., J. S. Irving, R. D. Olsen, E. A. Stull, and G. W. Witmer. 1986. Cumulative impact assessment: Evaluating the environmental effects of multiple human development. Argonne National Laboratory, Technical Memorandum ANL/EES-TM-309. Argonne, Illinois, 71 pp.

Barnard, W. D., C. K. Ansell, J. G. Hern, and D. Kevin. 1985. Establishing priorities for wetland management. *Water Resources Bulletin*, 21(6):1049–1054.

Barrows, R., D. Henneberry, and S. Schwartz. 1982. Individual economic incentives, the tax system and wetland protection policy: A study of returns to wetlands drainage in southeastern Wisconsin. Proceedings of the American Society of Agricultural Engineers, p. 26.

Batie, S., and C. C. Mabbs-Zeno. 1985. Opportunity costs of preserving coastal wetlands: a case study of a recreational housing development. *Land Economics* 61(1):1–9.

Beanlands, G. E., and P. N. Duinker. 1984. An ecological framework for environmental impact assessment. *Journal of Environmental Management* 18:267–277.

Bell, F. W., and V. R. Leeworthy. 1987. Economic demand for marinas and projected impact on wetlands. *Land Economics* 63(1):79–91.

Blumm, M. C. 1980. The Clean Water Act's Section 404 permit program enters its adolescence: An institutional and programmatic perspective. *Ecology Law Quarterly* 8:409–472.

Boland, J. 1983. The social value of tradable permits: The application of an asset utilization model. Pages 149–162 *in* E. F. Joeres and M. H. David (eds.), Buying a better environment. University of Wisconsin Press, Madison, Wisconsin.

CEQ (Council on Environmental Quality). 1978. Regulations for implementing the procedural provisions of the National Environmental Policy Act. 43FR5578-56007 November 29. 40 CFR Parts 1500–1508.

Clark, J., and C. Terrell. 1978. Effects on living resources and habitats, vol. III. Environmental planning for offshore oil and gas. The Conservation Foundation, for US Fish and Wildlife Service, Biological Services Program FWS OBS-77/14, 220 pp. National Space Technology Laboratories, NSTL Station, Mississippi.

Clean Water Act (CWA). 1977. Public Law 95-217; 33 U.S.C. 466, et seq.

Cohon, J. 1978. Multiobjective programming and planning. Academic Press, New York, 333 pp.

Contant, C. K., and L. Ortolano. 1985. Evaluating a cumulative impact assessment approach. *Water Resources Research* 21(9):1313–1318.

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. Leroe. 1979. Classification of wetlands and deepwater habitats of

the United States. US Fish and Wildlife Service Report No. FWS/OBS-79/31, 103 pp.

Dee, N., J. Baker, N. Drobny, and K. Duke. 1973. An environmental evaluation system for water resource planning. *Water Resources Research* 9:523–535.

Emery, K. M. 1986. Impact interaction potential. A basin-wide algorithm for assessing cumulative impacts from hydropower projects. *Journal of Environmental Management* 23:341–360.

Executive Order 11990. 1977. Protection of wetlands.

Farber, S., and R. Costanza. 1987. The economic value of wetlands systems. *Journal of Environmental Management* 24:41–51.

Forman, R. T. T., and M. Godron. 1986. Landscape ecology. John Wiley & Sons, New York, 619 pp.

Gilliland, M. W., and B. D. Clark. 1981. The Lake Tahoe Basin: A systems analysis of its characteristics and human carrying capacity. *Environmental Management* 5(5):397–407.

Gosselink, J. G., and L. C. Lee. 1987. Cumulative impact assessment in bottomland hardwood forests. Prepared by the Center for Wetland Resources, Louisiana State University, for Office of Federal Activities, US Environmental Protection Agency.

Haines, R. W. 1975. Wetland's reluctant champion: The Corps takes a fresh look at "navigable waters." *Environmental Law* 6:217–241.

Hardin, G. 1968. The tragedy of the commons. *Science* 162:1243–1248.

Harris, L. D. 1984. The fragmented forest. Island biogeography theory and preservation of biotic diversity. University of Chicago Press, Chicago, 211 pp.

Heimlich, R., and L. Langner. 1986. Swamp busting: Wetland conversion and farm programs. US Department of Agriculture, Economic Research Service. US Government Printing Office, Washington, DC.

Hill, D. 1977. Linear programming model to quantify economic, environmental, and social values for tidal marsh. Dissertation. Columbia University, New York.

Hirsch, A. 1988. The Regulatory Context for Cumulative Impact Research. *Environmental Management* 12:715–723.

Hobbs, B. F. 1985. Choosing how to choose: Comparing amalgamation methods for environmental impact assessment. *Environmental Impact Assessment Review* 5:301–319.

Hollick, M. 1981. The role of quantitative decision-making methods in environmental impact assessment. *Journal of Environmental Management* 12:65–78.

Horak, G. E., E. C. Vlachos, and E. W. Cline. 1983. Methodological guidance for assessing cumulative impacts on fish and wildlife. Prepared for Eastern Energy and Land Use Team, Office of Biological Services, Fish and Wildlife Service. Draft Final Report.

House, P. 1976. The quest for completeness. Lexington Books, D.C. Health, Lexington, Massachusetts, 245 pp.

House, P., and E. R. Williams. 1971. The carrying capacity of a nation. Lexington Books, D.C. Health, Lexington, Massachusetts, 356 pp.

Isaard W. 1972. Ecologic–economic analysis for regional development. The Free Press, Ne[illegible] pp.

Kahn, A. E. 1966. The tyranny of small decisions: Market failures, imperfections, and the limits of economics. *KYKLOS: International Review for Social Science* 19:23–45.

Keeney, R., and H. Raiffa. 1976. Decisions with multiple objectives: Preferences and value tradeoffs. John Wiley & Sons, New York, 569 pp.

Knetsch, J. L., and P. H. Freeman. 1979. Environmental and economic assessments in development project planning. *Journal of Environmental Management* 9(3):237–246.

Leopold, L. A., F. E. Clarke, B. B. Henshaw and J. R. Balsley. 1971. A procedure for evaluating environmental impacts. US Geological Survey Document No. 645.

Luken, R. A. 1976. Preservation versus development: An economic analysis of San Francisco Bay wetlands. Praeger, New York, 155 pp.

Maloney, M. T., R. T. Byrnes, and T. B. Yandle, Jr. 1977. Applications for South Carolina's wetlands of a general model of efficient solutions to externalities. Water Resources Research Institute, Report No. 70, Clemson University, Clemson, South Carolina, 150 pp.

McAllister, D. M. 1980. Evaluation in environmental planning. MIT Press, Cambridge, Massachusetts, 308 pp.

NEPA (National Environmental Policy Act). 1969. P.L. 91-190, 43 US Code 4321-4347.

New England River Basins Commission. 1978. Connecticut River cumulative impacts study. Prepared by Resource Analysis, Inc., Waltham, Massachusetts.

Nichols, R., and E. Hyman. 1982. Evaluation of environmental assessment methods. *ASCE Journal of Water Resources Planning and Management* 108(WR1):87–105.

Nixon, S. 1980. Between coastal marshes and coastal water—a review of twenty years of speculation and research on the role of salt marshes in estuarine productivity and water chemistry. Pages 437–525 *in* P. Hamilton and K. B. MacDonald (eds.), Freshwater wetlands; ecological processes and management potential. Academic Press, New York.

NRC (National Research Council). 1986. Ecological knowledge and environmental problem solving—concepts and case studies. Committee on the Applications of Ecological Theory to Environmental Problems. National Academy Press, Washington, DC, 388 pp.

NSF (National Science Foundation). 1979. A study of ways to improve the scientific context and methodology of environmental impact analysis. Prepared by School of Public and Environmental Affairs, Indiana University, Bloomington, Indiana, 453 pp.

Odum, H. T., and E. C. Odum. 1976. Energy basis for man and nature. McGraw-Hill, New York, 296 pp.

O'Neill, R. V., D. L. DeAngelis, J. B. Waide, and T. F. H. Allen. 1986. A hierarchical concept of ecosystems. Monographs in Population Biology 23. Princeton University Press, Princeton, New Jersey, 254 pp.

Ortolano, L. 1984. Environmental planning and decision-making. John Wiley & Sons, New York, 431 pp.

Pimm, S. L. 1982. Food webs. Chapman and Hall, London, 220 pp.

Power, G. 1978. The regulatory program of the US Army Corps of Engineers. Pages 19–40 *in* W. H. Queen (ed.), Physical alterations of coastal shorelines: An analysis of Chesapeake Bay shorezone development and regulation. Chesapeake Research Consortium, Annapolis, MD.

Preston, E. H., and B. L. Bedford. 1988. Evaluating Cumulative Effects on Wetland Functions: A Conceptual Overview and Generic Framework. *Environmental Management* 12:565–583.

Reppert, R. T., W. Sigleo, E. Stakhiv, L. Messman, and C. Meyers. 1979. Wetland values: Concepts and methods for wetlands evaluation. US Army Corps of Engineers. Institute for Water Resources, Research Report 79-R1, Fort Belvoir, Virginia, 109 pp.

Shabman, L. 1980. Economic incentives for bottomland conversion: The role of public policy and programs. Pages 402–412 *in* K. Sobol (ed.) Transactions of the 45th North American Wildlife and Natural Resources Conference. Wildlife Management Institute, Washington, D.C.

Shulstad, R. N., and R. D. May. 1979. Cropland converison study for the Mississippi Delta region. Report to resources for the future. Department of Agricultural Economics and Rural Sociology, University of Arkansas, Fayetteville, 181 pp.

Stakhiv, E. 1986. Achieving social and environmental objectives in water resources planning: Theory and practice. Pages 107–125 *in* W. Viessman, Jr., and K. E. Schilling (eds.), Social and environmental objectives in water resources planning and management. Proceedings of the Engineering Foundation Conference, American Society of Civil Engineers, New York, 326 pp.

Stakhiv, E. 1987. Environmental analysis in water resources planning. Pages 441–457 *in* W. O. Wunderlich and J. E. Prins (eds.), Water for the future: Water resources developments in perspective. Proceedings of the International Symposium on Water for the Future, Rome, Italy. A.A. Balkema, Rotterdam, The Netherlands.

Stavins, R. 1987. Conversion of forested wetlands to agricultural uses (executive summary). Environmental Defense Fund, Washington, DC, 72 pp.

US Army Corps of Engineers, Institute for Water Resources. 1977. Energetics and systems modeling: A framework for energy evaluation of alternative transportation modes. IWR Report 77-10. Fort Belvoir, Virginia, 173 pp.

US Army Corps of Engineers Institute for Water Resources. 1981. A handbook for cumulative impact analysis. Draft report, prepared by Dames and Moore, Inc., Fort Belvoir, Virginia.

US Congress. 1984. Wetlands: Their use and regulation. Office of Technology Assessment, OTA-0-026, Washington, DC.

US Water Resources Council. 1981. Analysis of methodologies for assessment of wetland values. Technical Report by the U.S. Army Waterways Experiment Station. US Government Printing Office. Washington, DC, 68 pp.

US Water Resources Council. 1983. Economics and environmental principles and guidelines for water and related land resources implementation studies. US Government Printing Office, Washington, DC, 137 pp.

Vlachos, E., and D. W. Hendricks. 1976. Secondary impacts and consequences of highway projects. US Department of Transportation. DOT-05-50043, Washington, DC.

Waide, J. 1981. Wetlands stability. *In* Analysis of selected wetlands functions and values. Draft Report 81D-01. US Army Institute for Water Resources, Fort Belvoir, Virginia.

Walker, R. A. 1973. Wetlands preservation and management of Chesapeake Bay: The role of science in natural resource policy. *Coastal Zone Management* 1(1):75–101.

Walker, R. A. 1974. Wetlands preservation and management: A rejoinder—economics, science and beyond. *Coastal Zone Management* 1(2):227–233.

Webster, J. R., J. B. Waide, and B. C. Pattens. 1975. Nutrient recycling and the stability of ecosystems. Pages 1–27 *in* F. G. Howell, J. B. Gentry, and M. H. Smith (eds.), Mineral cycling in southeastern ecosystem. ERDA Symposium Series, CONF-740513. US Energy Research and Development Administration, Washington, DC.

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This article documents research that was conducted under the auspices of the U.S. Environmental Protection Agency (USEPA). As an arm of the government, the USEPA has a paid up, non-exclusive, irrevocable, worldwide license to reproduce, prepare derivative works, and distribute to the public all of the material contained herein, and to grant others acting on its behalf the right to do so. The USEPA grants to the National Technical Information Service, Department of Commerce, the right to act as its agent in the distribution of this material.